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# Measuring growth index in a universe with massive neutrinos: A revisit of the general relativity test with the latest observations

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ABSTRACT

We make a consistency test for the general relativity (GR) through measuring the growth index $\gamma$ in a universe with massive (sterile/active) neutrinos. We employ the redshift space distortion measurements to do the analysis. To constrain other cosmological parameters, we also use other cosmological measurements, including the Planck 2015 cosmic microwave background temperature and polarization data, the baryon acoustic oscillation data, the type Ia supernova JLA data, the weak lensing galaxy shear data, and the Planck 2015 lensing data. In a universe with massive sterile neutrinos, we obtain $\gamma = 0.624^{+0.055}_{-0.050}$, with the tension with the GR prediction $\gamma = 0.55$ at the $1.48\sigma$ level, showing that the consideration of sterile neutrinos still cannot make the true measurement of $\gamma$ be well consistent with the GR prediction. In a universe with massive active neutrinos, we obtain $\gamma = 0.663 \pm 0.045$ for the normal hierarchy case, $\gamma = 0.661^{+0.044}_{-0.050}$ for the degenerate hierarchy case, and $\gamma = 0.668^{+0.045}_{-0.051}$ for the inverted hierarchy case, with the tensions with GR all at beyond the $2\sigma$ level. We find that the consideration of massive active neutrinos (no matter what mass hierarchy is considered) almost does not influence the measurement of the growth index $\gamma$.



## 1. Introduction

The current astronomical observations have indicated that the universe is undergoing an accelerated expansion [1–5]. To explain this accelerated expansion, in the context of general relativity (GR), the so-called dark energy (DE), an unknown component with negative pressure, is proposed [6–10]. On the other hand, the modification of gravity (MG) can also account for the accelerated expansion by mimicking the behavior of DE within GR for the whole expansion history at the background level [11–13]. Both of them can in principle describe the same expansion, but they are different in nature. To distinguish between MG and GR, the precise large-scale structure (LSS) measurements are required because they have different histories of growth of structure.

A way to describe the growth of scalar (density) perturbations in non-relativistic matter component (cold dark matter and baryons) is provided by the parametrization $f(a) = \Omega_{\rm m}(a)^{\gamma}$, proposed in Ref. [14], where $f(a) \equiv d\ln\delta(a)/d\ln a$ is the growth rate for linear perturbations, $\Omega_{\rm m}(a) = \Omega_{\rm m} H_0^2 H(a)^{-2} a^{-3}$ is the fractional matter density, and $\gamma$ is called the growth index. Both of the growth index and the evolution of matter density depend on the specific model (for details see the latest review [15]). For dark energy models with slowly varying equation of state, within GR, an approximation of $\gamma \approx 0.55$ is derived. For example, based on the $\Lambda$CDM model, $\gamma = 6/11 \approx 0.545$ is given [16]. However, for MG models, different theoretical values of $\gamma$ are derived; e.g., for the Dvali–Gabadadze–Porrati (DGP) model, $\gamma \approx 0.68$ is obtained [17–19].

The growth index in a cosmological model can be constrained by using the redshift space distortion (RSD) observation. RSD is a significant probe for the growth of structure, which provides an important way of measuring the growth rate $f(z)$ at various redshifts. In practice, RSD measures the product of $f(z)$ and $\sigma_8(z)$, namely, $f(a)\sigma_8(a) = d\sigma_8(a)/d\ln a$, where $\sigma_8(z)$ is the root-mean-square mass fluctuation in a sphere of radius $8h^{-1}$ at the redshift $z$. However, using RSD to constrain the growth index (based on the $\Lambda$CDM model), it is found that there is a deviation of the $\gamma$ value from the GR's theoretical prediction of $\gamma \approx 0.55$ at the 2–3$\sigma$ confidence level (see, e.g., Ref. [20]). Recently, Gil-Marin et al. [21] used the latest BOSS CMASS and LOWZ DR12 measurements combined with the Planck 2015 temperature and polarization spectra to constrain $\gamma$, and they obtained $\gamma = 0.719^{+0.080}_{-0.072}$, which reveals a

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beyond 2.5$\sigma$ tension with the GR prediction. The similar situation can be found in the previous studies [22,23].

It can be noticed that the measurements of $\gamma$ have been always higher than the GR prediction. That is to say, the actual observed growth of structure is faster than that predicted by GR. One way to reconcile them is to consider massive (active or sterile) neutrinos in the cosmological model, since the free-streaming property of neutrinos could help suppress the growth of structure on small scales. In 2014, two of the authors of the present paper (Jing-Fei Zhang and Xin Zhang) and another collaborator (Yun-He Li) [24] considered this scheme, and they found that if massive sterile neutrinos are involved in the cosmological model, then the constraint value of $\gamma$ and the theoretical prediction of $\gamma = 0.55$ will become well consistent.

In Ref. [24], Zhang, Li, and Zhang used the RSD data in combination with other observations (at that time) including the cosmic microwave background (CMB) anisotropy data from the Planck 2013 temperature spectrum [25] and the WMAP 9-yr polarization data [26], baryon acoustic oscillations (BAO) measurements from the 6dFGS [27], SDSS DR7 [28], WiggleZ [29], and BOSS DR11 [30] surveys, the Hubble constant $H_0$ measurement with the value of $73.8 \pm 2.4$ km/s/Mpc [31], the Planck Sunyaev–Zeldovich cluster counts data [32], and the cosmic shear data from CFHTLenS survey [33], to constrain $\gamma$, and they obtained $\gamma = 0.584^{+0.047}_{-0.048}$, well consistent with the prediction value of GR of $\gamma \approx 0.55$. See Refs. [34–50] for other previous works discussing the issue of using massive sterile neutrinos to relieve tensions among cosmological observations.

However, it should be pointed out that it is the time to revisit this issue with the latest cosmological observations. In the past years, numerous more accurate data were released, which would update the previous results derived in Ref. [24] and even would change the conclusive statements.

In this paper, we will revisit the study of the constraints on the growth index, based on the $\Lambda$CDM cosmology with massive (sterile/active) neutrinos, using the latest cosmological measurements, including the Planck 2015 temperature and polarization power spectra and the latest RSD data. Moreover, since the lensing observations including the weak lensing and the CMB lensing can capture the effects of massive neutrinos on the matter power spectra, they can provide useful constraint on the neutrino mass. In addition, the growth index is related to not only the structure's growth, but also the expansion of the universe, and thus the independent geometric observations such as BAO and type of Ia supernova (SN) are also needed. We will use these latest observations to study the measurement of the growth index $\gamma$.

The paper is arranged as the following. In Sec. 2, we introduce the method and observational data used in this paper. In Sec. 3, we report the results of the consistency test of GR. In Sec. 4, we will make a conclusion for this work.

## 2. Method and data

In this paper, we place constraints on the growth index $\gamma$ in the $\Lambda$CDM cosmology with massive (sterile/active) neutrinos with the latest observations. Within GR, as long as the equation-of-state parameter of DE is slowly varying, the theoretical predictions of $\gamma$ for DE models are almost the same, i.e., $\gamma \approx 0.55$. Thus, in this paper, we only consider the $\Lambda$CDM cosmology.

For the base $\Lambda$CDM model, there are six base parameters, which are the baryon density $\Omega_b h^2$, the cold dark matter density $\Omega_c h^2$, the ratio of the angular diameter distance to the sound horizon at last scattering $\theta_*$, the reionization optical depth $\tau$, and the amplitude $A_s$ and the tilt $n_s$ of the primordial scalar fluctuations.

To constrain the growth index $\gamma$, we use the parametrization $f(a) = \Omega_m(a)^\gamma$ to describe the density perturbations in the $\Lambda$CDM cosmology, and thus we introduce an extra parameter $\gamma$ into the model. We use the RSD measurements of $f(z_{\rm eff})\sigma_8(z_{\rm eff})$ to set constraints on $\gamma$. We follow the procedure of Sec. 9.1 in Ref. [23] to include $\gamma$ as an additional parameter. Here, it is helpful to briefly describe how the parameter product $f_\gamma(z_{\rm eff})\sigma_{8,\gamma}(z_{\rm eff})$ is derived in the theoretical calculations by the following two steps: (i) Since in this description the value of $\sigma_8(z_{\rm eff})$ depends on $\gamma$, we have to recalculate this value by using the parametrization of $f_\gamma(a_{\rm eff}) = \Omega_m(a_{\rm eff})^\gamma$. We first calculate the growth factor, $D(a_{\rm eff}) = \exp\left[-\int_{a_{\rm eff}}^1 da' f(a')/a'\right]$, where $a_{\rm eff}$ is the scale factor at the effective redshift $z_{\rm eff}$. Then, we derive $\sigma_{8,\gamma}(z_{\rm eff})$ by the extrapolation from the matter dominated epoch to the effective redshift, $\sigma_{8,\gamma}(z_{\rm eff}) = \frac{D_\gamma(z_{\rm eff})}{D(z_{\rm hi})}\sigma_8(z_{\rm hi})$, where $\sigma_8(z_{\rm hi})$ is calculated at $z_{\rm hi} = 50$ which is in the deep matter-dominated regime, where $f(z) \approx 1$. (ii) We calculate the growth rate by using the parametrization $f_\gamma(z_{\rm eff}) = \Omega_m(z_{\rm eff})^\gamma$. Thus, now, we can obtain the parameter product $f_\gamma(z_{\rm eff})\sigma_{8,\gamma}(z_{\rm eff})$ in the numerical calculations.

If we further consider massive neutrinos in cosmology, we need to add the total neutrino mass $\sum m_\nu$ for the case of active neutrino and the effective mass $m_{\nu,\rm sterile}^{\rm eff}$ and the effective number of relativistic species $N_{\rm eff}$ for the case of sterile neutrino.

We make our analysis by employing several important cosmological probes. We use the Planck 2015 full temperature and polarization power spectra at $2 \le \ell \le 2900$. We refer to this dataset as "Planck TT, TE, EE" (note that we do not use "+lowP", as the Planck collaboration used, for simplicity). In addition to the CMB dataset described above, we consider the combination with the following cosmological measurements:

- The BAO data: We use the BAO measurements from the 6dFGS ($z = 0.1$) [27], SDSS-MGS ($z = 0.15$) [51], LOWZ ($z = 0.32$) and CMASS ($z = 0.57$) DR12 samples of BOSS [52]. Note that we exclude the BOSS DR12 results from BAO likelihood when the RSD measurements of DR12 are used in the data combination in this paper.
- The SN data: For the type Ia supernova observation, we adopt the "JLA" sample, compiled from the SNLS, SDSS, and the samples of several low-redshift SN data [53].
- The RSD data: We employ RSD measurements at 11 redshifts, which are 6dFGS ($z = 0.067$) [54], 2dFGS ($z = 0.17$) [55], WiggleZ ($z = 0.22, 0.41, 0.60$, and $0.78$) [56], SDSS LRG DR7 ($z = 0.25$ and $z = 0.37$) [57], BOSS CMASS DR12 ($z = 0.57$) and LOWZ DR12 ($z = 0.32$) [21], and VIPERS ($z = 0.80$) [58] samples.
- The WL and CMB lensing data: We use the cosmic shear measurement of weak lensing from the CFHTLenS survey, and we apply the "conservative" cuts for the shear data according to the recipe of Ref. [59]. We denote the dataset of shear measurement (weak lensing) as "WL" in this paper. We also use the CMB lensing power spectrum from the Planck 2015 lensing measurement [60], which is denoted as "lensing" in this paper.

The analysis is done with the latest version of the publicly available Markov-Chain Monte Carlo package `CosmoMC` [61], with a convergence diagnostic based on the Gelman and Rubin statistics.

In this paper, tensions between different observations for some cosmological parameters will occasionally be mentioned, so it is helpful to clearly describe how to estimate the degree of tension between two observations for some parameter in this place. Assume that, for a parameter $\xi$, we have its 68% confidence level ranges $\xi \in [\xi_1 - \sigma_{1,\rm low},\ \xi_1 + \sigma_{1,\rm up}]$ from an observation (O1) and